STUDIES FOR STUDENTS.

CONDITIONS OF SEDIMENTARY DEPOSITION.

EROSION.

Erosion consists of fragmental reduction and abrasion of rock masses, chemical disintegration of rocks and transportation. The three sub-processes may be called rock-breaking, rock-decay and transportation. They are conditioned by declivity, lithologic character and climate.

ROCK-BREAKING.

Favorable conditions:

(*a*) Steep slopes.
(*b*) Bare rocks.
(*c*) Cleaved and jointed rocks.
(*d*) Alternation of hard and soft beds.
(*e*) Rapid changes of temperature.
(*f*) Aridity and high winds.
(*g*) Abundant rainfall, in the absence of vegetation.
(*h*) Sea cliffs.

Products: Shingle, gravel and sand of mixed mineralogical composition.

ROCK-DECAY.

Favorable conditions:

(*a*) Gentle slopes.
(*b*) Porous soil.
(*c*) Soluble rock constituents.
(*d*) Carbonic acid and other acids of organic decay.
(*e*) Abundant rainfall in the presence of vegetation.
(*f*) Prolonged transportation of gravel and sand.

Products: Rock cores of disintegrated masses, sand, (chiefly quartz-sand), residual clays, and lime, magnesia, iron, etc., in solution.

TRANSPORTATION.

Favorable conditions:

(*a*) Steep slopes.
(*b*) Abundant rainfall.
(*c*) Absence of vegetation.
(*d*) Floods
(*e*) Fine detritus.

By comparison of the statements of favorable conditions for rock-breaking, rock-decay and transportation it becomes apparent that breaking and decay are favored by opposite conditions in nearly all respects, while breaking and transportation are most efficient under like conditions. But breaking promotes decay, and decay aids transportation, by reducing the size of the particles to be decomposed and carried, and the maximum effect of erosion is probably attained when rock-breaking is active among greater elevations, and rock-decay and transportation are both proceeding energetically on lower slopes.[1]

The amount of material furnished by erosion is an important consideration in reference to the rate of accumulation of sediments over a given area, and is a condition not to be overlooked in comparing thicknesses of deposits with the lapse of geological ages.

SEQUENCE OF SEDIMENTS.

Shingle, gravel, sand, clay and silt are products of erosion of rock masses. They are produced either by mechanical breaking or by chemical disintegration. These two subprocesses of the general process of erosion are favored by unlike conditions. Those conditions which render breaking most efficient are unfavorable to immediate disintegration; and those conditions which promote disintegration limit breaking. Breaking, the reduction of a rock mass to small pieces, is usually

[1] Gilbert, Henry Mts. p. 105.

the antecedent of disintegration, of decay, but the two are not most efficiently active at the same time. Now their products differ. Rock breaking yields shingle, gravel, coarse sand of mixed mineralogical composition, and no chemical solutions. Rock-decay yields directly no shingle or gravel, but produces sand, chiefly quartz-sand, clay, silt and chemical solutions. Hence, if the products of rock-breaking are deposited unchanged in the sea, there will result one class of sediments from which we may infer corresponding conditions of erosion of the parent land; and if the products of rock-decay are deposited we must infer other conditions of erosion.

Declivity is the chief factor which determines either rock-breaking or rock decay. Rock breaking occurs on steep slopes, that is, among hills or mountains; rock-decay takes place chiefly on gentle slopes, that is, in valleys or on plains. Hence the sediments may indicate the topographic phase of the parent-land.

They may indicate topographic phase, not permanent topographic character, for relief of the land surface is transient. The steeps of mountains become the slopes of hills, the hill slopes sink to plains and plains to base-level; and erosion pauses till renewed by uplift. So the conditions of rock-breaking pass into those of rock-decay, and the product of the two processes may appear in sediments, the older gravel and sand beneath the younger sandy clay and clay.

The possible sequence of unlike sediments does not stop with the finer mechanical products of disintegration; chemical solutions may be related to chemical or organic deposits, and these have their place among strata. The amount of lime and magnesia carried annually from a given land area is directly related to the efficiency of rock-decay, and so among other factors to slope. Rock-decay is limited on the one hand by declivities, which promote the rapid running off of rainfall, and on the other hand by the accumulation of a deep covering of soil, which prevents percolation. Other things being equal, it is probably most efficient during the period corresponding with the life of low hills and sloping plains. If at any time chemical solutions from

the land determine the deposition of calcareous formations they will do so most efficiently during this topographic phase, and in the absence of mechanical sediments the corresponding deposits will be limestones or dolomites. As the topographic phase passes to its close and the sloping plains sink to base-level, the power of streams to transport mechanical sediment fails, and rivers finally carry only silt in lessening proportion; hence the upper portions of a great limestone deposit may be less clayey than the lower. Furthermore, the mantle of residual clays, accumulating upon the extended base-level, will check solution, and thus, in so far as the deposition of limestone is influenced by contributions from the land, will limit the growth of the formation; and with the cessation of both mechanical and chemical supply, terrigenous deposits will cease to form beneath the sea. Then, while these conditions endure geologic ages may pass without record in sediments unless there is a marine source of supply.

Thus far this statement has tacitly assumed a constant relation of elevation between coast and ocean. Assume that the long quiet, which has been necessary for the reduction of a mountain range to base-level and the deposition of the corresponding sediments, is interrupted by sinking or heaving of the land area. The surface is low, flat and covered by a mantle of residual sand and clay intimately mingled. Moderate subsidence must lead to extensive transgression and the invading sea, margined by tide flats, will spread arenaceous, clayey deposits, bearing the marks of shallow water formations and resting unconformably upon the ancient rocks. If the residual soil be red, the sediments will be of similar color, since the process of deposition on tide flats does not involve much attrition and the ferruginous coating of the grains will remain.[1] The base of the deposit may be a zone of transition, composed of cores of undecomposed rocks, imbedded in more or less re-arranged products of partial decomposition.[2]

[1] Bull. U. S. G. S. No. 52. I. C. Russell, Subaërial Decay of Rocks and Origin of Red Color of Certain Formations.

[2] R. Pumpelly. The Relation of Secular Rock Disintegration to Certain Transitional Schists. Bull. Geol. Soc. of America. Vol. II., p. 209.

Or, on the other hand, moderate uplift of the base-leveled continent, must cause the revived streams rapidly to sweep into the sea the mass of insoluble clay and sand which formed the residual mantle. Thus the limestone deposits will be succeeded by a thickness of shales of a more or less arenaceous or clayey character.

From these considerations it follows that a complete topographic cycle may be related to a sedimentary sequence composed of a sandy base, a limestone middle and a shale top. Newberry first noted the frequent recurrence of this sequence, and sought an explanation in conditions related simply to the sea; its advance, presence and retreat. When he made his generalization the base-level had not been recognized as a result of continued erosion, nor had Gilbert analyzed the process of erosion; and Davis had not described a topographic cycle. These contributions to the science have widened the field of inference, and the topographic phase of the land can no longer be disregarded in the discussion of the deposits of the sea.

But it should not be forgotten that the inference from sediments should be confined to the topographic phase of a belt of land extending back from the shore to a moderate distance only. The products of rock-breaking disintegrate during prolonged transportation and mountains remote from the coast are not indicated in deltas of great rivers. A student of the deposits of the Mississippi would not infer the height of the Rocky mountains, but the sands of the Klamath river bear witness to the nearness of the coast range.

The analysis and discussion of conditions which govern the character of the material contributed from land to sea might be extended in detail, and illustrated by descriptions of sediments in existing rivers, but the subject is worthy of independent treatment.

SEDIMENTATION.

Sedimentation consists of three sub-processes, sorting, distribution and deposition. These are effected by waves and undertow, tides, winds and oceanic currents and are modified

by the relation of volume of sediment to the force of waves or currents. If the analysis be based on the sub-processes and conditions which favor them, it may be stated and discussed as follows:

SORTING.

The conditions under which sorting is more or less efficiently carried on are three in number.

Favorable conditions:

(*a*) Vigorous wave action accompanied by strong undertow.

(*b*) Prolonged transportation in consequence of deep water and continuous currents.

(*c*) Moderate volume of sediments.

The conditions under which sorting is not accomplished are the reverse of these, namely:

Unfavorable conditions:

(*a*) Feeble or diffused wave action.

(*b*) Concentrated deposition.

(*c*) Excessive volume of sediments.

It will be profitable briefly to discuss these positive and negative conditions.

(*a*) *Vigorous wave-action.*—The force of waves is determined by their fetch and the strength of winds. In the study of modern beaches the latter is important, since it controls the form and the greatest storm[1] fixes the maximum size of detritus moved; but in considering fossil beaches as strata we deal with sands which have been so rearranged during submergence that the beach form is lost. However the former condition, the fetch of the waves is more constant, and the force of the waves determined by it may be inferred from the nature of the beach deposits.

The efficiency of waves of a given force is determined by the concentration of their blows, and this is conditioned by the slope against which they break. If relatively deep water prevails

[1] For full discussion of wave erosion and deposition, see Lake Bonneville, by G. K. Gilbert. Monograph 1, U. S. C. S.

to the shore, whatever force the waves may have is expended at the water's edge. On a bold coast they carve sea-cliffs and grind shingle with sand. Such are the coasts of New England, Oregon, California, and of all the Pacific side of South America. The resulting sediments are composed of worn but fresh rock fragments and thus bear witness to rapid mechanical erosion, like the products of rock breaking on steep declivities. On a shore of incoherent materials waves stir, wash and separate fine and coarse, light and heavy particles. Under favorable conditions of depth of water and long fetch, waves thus sort a heterogeneous mass of gravel or of residual sand and clay more efficiently than any other agent, and leave clean cross-stratified beach sand and gravel with boulders, while the finer materials are swept away. The southeastern shore of Long Island presents a conspicuous example of this, and the westward drift of the beach-sands is illustrated in the fact that shingle beaches prevail toward the eastern end of Montauk point, and the sands there washed from the bluffs of glacial gravel form long barriers along the coast to the westward.

If, on the other hand, waves break in shallow waters at a distance from shore they there build a barrier, and the height to which they build it above high tide is the measure of their maximum power during great storms. Within the barrier then extends a lagoon. The whole Atlantic coast from Long Island to Florida is thus fringed by the features of prevalent wave action, due to the great fetch from off the ocean and the gradual slope of the continental platform.

(*b*) *Prolonged transportation.*—Sorting is also accomplished to some extent, though less perfectly, by deep water and continuous currents. Sediments settle unequally according to size and specific gravity of particles; therefore the largest and heaviest reach bottom first, the finer and lighter later, and the finest and lightest last. If the conditions of supply or current be intermittent over any area then each incident of deposition will be marked by a layer composed of coarsest grains below and finest grains on top. This is the nature of deposition in tidal estua-

ries. If, on the other hand, currents be continuous and constant, the zones of sand, clay and silt deposits will occur each beyond the former. But this is a question of distribution as well as of sorting of sediments.

(*c*) *Moderate volumes of sediments.*—Sediments are also more or less completely sorted by waves or currents according to the relation between the volume of sediment and the force of the sorters. When waves breaking upon a coast have only the product of wave erosion to handle they sort most completely; the material is washed again and again until no trace of clay remains mingled with the sand grains; and the under-tow, burdened only with the clay washed out by the waves and the fine products of abrasion, carries them all away. But where a river pours out a large volume of sediment, and waves or currents are consequently overloaded, both sorting and transportation fail to a greater or less degree. Deposition takes place too rapidly for the separation of fine from coarse and the deposit is of mixed character. The effect of waves is then seen in ripple-marked and ill-assorted beds of tide flats.

DISTRIBUTION.

The conditions under which sediments are more or less widely distributed, depend upon movement of the waters and the nature of the sediment; those favorable to distribution are:

Favorable conditions :

(*a*) Efficient wave action prevailing from one direction oblique to the shore.
(*b*) Continuous currents.
(*c*) Uniform or gradually increasing depths of water.
(*d*) Fine or light sediment.

The reverse of these conditions favor deposition, and will be discussed in that connection.

(*a*) *Efficient, oblique wave action.*—Distribution of shore drift is fully discussed by Gilbert, and has already been referred to in stating the effect of sorting by waves of the Atlantic on

the south shore of Long Island, and the formation of barriers of wave-washed sand.

(*b*) *Continuous currents.*—Distribution by continuous currents is the condition usually assumed as having controlled the arrangement of sediments in seas of past geologic periods. In consequence of the sorting which results from different rates of settling clay is carried beyond sand, and silt is distributed more widely than clay. The prevailing current, which thus distributes, is under-tow more or less checked and assisted by tides. If the submarine slope descends from the shore steeply into oceanic depths, the force of undertow must rapidly be dissipated, but pebbles and sand move easily down the steep incline, and form a sequence of continually smaller particles, which is usually not very extended. This is the case on the western coast of South America. If, on the other hand, the seaward slope is very gentle, undertow loses force more gradually and fine sands may occur to great distances from the shore, with clay and silt deposited beyond them. This is the case off the Atlantic coast of the United States where tides probably form a powerful alternating influence; there the continental plateau is covered with sand to its outer rim, as is shown by soundings by the Coast Survey. But the force of undertow is determined in the first place by the force of waves, and it can be effective in distributing only where waves are powerful. It fails in limited seas except in a very narrow zone along shore.

Ocean currents also distribute sediments very widely. The terrigenous deposits of the Bay of Bengal and Arabian sea, mapped by Murray,[1] covering 1,600,000 square miles, owe their wide spread distribution apparently to the ocean currents which circulate east and west alternately with the changes of season in these great bays.

(*c*) *Uniform depths.*—Changes in depth of water affect the velocity of a current and thus modify its power to distribute sediment. Narrowing channel or shallowing water may cause a

[1] Scottish Geogr. Mag., Vol. V. No. 8, Aug. 1889.

current to scour and take on more load; but broadening channel or deepening water tends to cause it to deposit. The Gulf stream scours the straits of Florida and the Blake plateau, but deposits a silt bank on the lee side of the latter.[1] Only in the broad expanse of deep water does it widely distribute sediment.

(*d*) *Size of particles.*—Fine or light sediment is most widely distributed. The "blue muds" which form the terrigenous deposits beyond the littoral zone consist of particles of an average diameter of .05 mm.

Deposition occurs whenever a body of water becomes overloaded with substances in suspension or in solution. According to the condition which determines the result the deposits may be classified as mechanical, chemical and organic.

MECHANICAL DEPOSITION.

Favorable Conditions:

(*a*) Arrest and retreat of waves; beaches and sand deposits from undertow.
(*b*) Current entering still water and slowing; lake-deposits.
(*c*) Alternating currents in fresh and salt water; estuarine deposits.
(*d*) Rise of salt water surface at a river's mouth in consequence of winds, long continued from one direction; delta of the Mississippi.
(*e*) Flotation of fresh water on salt; bars of the Mississippi.
(*f*) Floculation of sediments in salt water.
(*g*) Expansion and diffusion of a current in rapidly deepening water; silt deposits on the edge of continental plateaus.
(*h*) Final subsidence from oceanic circulation.

Arrest of Waves.—(*a*) Beaches are formed where waves break. The rotary oscillation which constitutes waves in deep water becomes a motion of translation when the water shallows sufficiently and the mass of the broken wave, rushing forward,

[1] Agassiz. Three Cruises of the Blake. Bull. Mus. of Comp. Zoölogy. Harvard College. Vol. XIV.

carries up material stirred from the bottom. The finer particles are swept back by the undertow, the coarse are placed by the greater waves beyond the reach of the lesser. Thus waves, constantly in advancing, take material from the lower part of the slope to carry it up, and in retreating sweep back more or less of their load with them. If the slope be gentle they thus take from the lower to add to the upper part, and therefore they increase the declivity until the seaward profile becomes so steep that the load carried in retreat balances that advanced. This is the profile of equilibrium, which waves perpendicular to the trend of the beach do not change, unless they are of unusual force. Waves oblique to the beach-slope, scour, transport and deposit the same sands repeatedly, and if the oblique advance be prevailingly from one direction the effect is to move the beach longitudinally. Then the beach, in any one section, continues, while the supply of sand is continuous; but when the supply ceases the beach is gradually moved onward in the direction of the prevailing wave action, and the material beneath the beach sands is exposed to wave erosion.

A beach itself is but a narrow zone; it cannot constitute a wide-spread formation any more than a line can constitute a plane. But if a line be moved in one direction parallel to itself it will develop the plane, and in the same manner if a beach advances landward it may spread a formation. This advance may be a result of wave erosion, which carving a sea cliff on a bold shore planes a surface of marine denudation. The beach deposit is then a basal conglomerate. Or, the land reduced to a low surface by subaërial erosion may subside slightly in reference to sea level, and the sea, transgressing, will rearrange the superficial formations. If the waves have power to handle the material the sea is margined by beach sands. If they cannot efficiently sort it the land will merge in tide-flats with the water.

A beach is not only narrow, it is also shallow; waves build on the surface over which they break, and the height to which they may build does not exceed a few feet. Therefore, beach deposits cannot form thick strata.

The undertow rolls coarser sand and pebbles down the slope of the bottom, and carries out in suspension silt and clay with more or less fine sand. The rolling of coarser sands is promoted by a steep slope. The transportation of finer sands depends on the endurance of the undertow of a given initial strength; and this endurance will be the greater the more gradual the seaward slope and the stronger the tides. The amount of sand thus deposited is limited only by the supply, and sandy strata may, therefore, attain great thickness and have great extent seaward from a fixed beach line. If the coast be continually maintained by uplift or renewed by volcanic flows the work of the waves may be of like duration and the record will be correspondingly voluminous. Professor Chamberlin mentions the great conglomerates of Lake Superior in this connection.

Beach deposits, strictly speaking, are usually of quite coarse sand, clean and characterized by marked and irregular cross-stratification. Sand deposits from undertow graduate from clean to muddy sands, becoming ever finer seaward, and are horizontally bedded or massive.

Therefore the interpretation which may be put on strata, deposited by the arrest and retreat of waves, are:

(1) A basal conglomerate is significant of an horizon of wave erosion, due to transgression of the sea and probable subsidence of the land. If the basal contact be clean and sharp the waves probably carved a shore cliff in hard rocks. If, between the parent rock and the later sedimentary formation, there be a zone of transition composed of boulders, sand and clay of mixed mineral composition, the waves probably rearranged the cores and finer products of a surface of partial subaërial rock decay. A basal conglomerate of any variety is a definite proof of an unconformity by erosion; it is often the only fact by which such an unconformity can be distinguished from an overthrust fault.

(2) A deposit of clean sands is proof of the former existence, somewhere, of a beach on which they were washed; but the place of deposit may have been remote from the line of the beach. Coarseness of grain suggests proximity of land and vice

versa, but such suggestions need to be qualified by considering the probable fetch of the waves, the corresponding initial strength of the undertow and the declivity of the seaward slope.

A thin stratum of coarse cross stratified sands may represent a transgression by a beach-building sea over a subsiding land. A thicker stratum may have been formed by deposits from undertow behind a stationary or advancing beach line, and if such a deposit shows cross-stratification throughout, it was washed by conflicting currents, probably tidal, during its accumulation.

The deposition of beach-washed sands is consistent with constant or subsiding level of the land in relation to the sea. It does not appear that it is likely to occur during uplift from the sea except in the comparatively rare case of the rapid elevation of a bold coast range with preponderance of rock-breaking over rock-decay.

The occurrence of a stratum of sandstone is not evidence that during its formation the land furnished no other detritus. If the sands be of mixed mineralogical composition, bold declivities on land and prevalence of rock-breaking are indicated; but if the sands be chiefly quartzose it is more probable that the waves have sorted the waste of a residual mantle.

Quiet Water.—(*b*) When a current enters a body of quiet fresh water, unvexed by tides or winds, as a stream enters a lake, the inertia of the greater mass and the diffusion of the stream in the greater volume checks the current, and it drops whatever sediment it may have carried. The laws of this simple case can be formulated mathematically, and Babbage has calculated the distance to which sediments of an assumed character would be transported by a river current of assumed velocity entering a salt-water body, whose bottom has an assumed slope; he neglects the difference of density between fresh and salt water, and assumes an off-shore current equal to that of the river at its mouth.[1] The conclusion is determined in advance, and cannot be applied to the interpretation even of lake sediments, since the assumed conditions of sediment and current are hypo-

[1] Hand Book of Physical Geology, 1884. A. J. Jukes-Browne, p. 185.

thetical. An existing case, which approaches the conditions assumed by Babbage, is that of the Rio Uruguay, which is described by Revy.[1]

"The little town of Higueritas, also called Nueva Palmira, is situated in latitude 33° 52′ S., long. 58° 23′ W., in the Banda Oriental, at the junction of the Uruguay with various branches of the Parana, all of which discharge jointly their volume into the La Plata. Three miles below Higueritas, at Punta Gorda, the La Plata proper commences; three miles above Higueritas the Uruguay opens into a lake from 4 to 6 miles wide and about 56 miles long. There are no islands on this lake, although, with the exception of a deep channel half a mile wide of steep sides and submerged, the lake is shallow; it may be called the estuary of the Uruguay. A little above Fray Bentos, 58 miles from Higueritas, the first islands appear within the lake; and, their number soon increasing, we enter the delta of the Uruguay, which for 25 miles more retains the width of the lower lake, breaking, however, up into a great number of large and small islands, until, a little below Paysandu, the river proper commences within a confined channel. At Paysandu, a commercial town of importance, 125 miles from Higueritas, the delta of the Uruguay commences. At Fray Bentos the visible delta terminates; and from the latter place to the La Plata the future delta of the Uruguay is now in course of formation. . . . .

. . . . During the survey of the Uruguay there was a periodical rise of the river, viz., on February 3, 1871, and a sample of water was taken on that day at the Salto section, about 200 miles above Higueritas. The water was turbid, of deep brown color; and the analysis of the sample showed that it contained one part by weight of solid matter in suspension in 9524 parts of water. There was no perceptible change in the color of the water or in its analysis, until we reached Fray Bentos [142 miles below Salto] on the 5th February, 1871, and here it contained 1 part solid matter in 11,200 of water by weight in suspension. At Higueritas, on the same day, the waters of the Uruguay ap-

[1] Hydraulics of Great Rivers. J. J. Revy, pp. 134–135.

peared clear, and we could only trace one part of solid matter held in suspension by 25,925 of water. Nothing could more forcibly illustrate the formation of deltas. The river retains matter held in suspension by its water within its ordinary channel as long as its velocity is maintained; as soon as it enters a lake or an estuary checking regular currents, the matter held in suspension is dropped."

That is to say, in flowing 142 miles in its navigable channel and through its delta the river dropped about 15 per cent. of the load which it bore at Salto; and beyond the delta in still water it dropped 48 per cent. more; leaving it but 37 per cent. of the original load to be carried past Higueritas to the estuary of the La Plata. Or stating the proportions in terms of the sediment brought through the delta to the head of the lake, 57 per cent. was deposited and 43 per cent. escaped. It would be desirable to determine in what ratio the deposit is made in the upper and lower reaches of the lake, but Revy gives no data between Fray Bentos and Higueritas. He states however that the lake is without islands, although it is shallow with the exception of a deep channel half a mile wide; but just above Fray Bentos islands indicate the present front of the delta. The occurrence of these advance elements of the delta only in a limited distance indicates that the bulk of deposition is on the delta's front, and that the sediment which passes beyond is that which the slower current of the lake can hold in suspension.

The deposits of the extinct lakes Bonneville and Lahontan have been fully described by Gilbert and Russell, but the lake beds of the west still present rich fields for study of deposition under simple conditions in fresh and salt water.

(*c*) *Alterations of Current.*—When a land-locked water body is open to the ocean it is subject to influx and reflux of tides, but the rivers pouring into it may possess volume sufficient to exclude salt water; it is then a fresh-water estuary, which receives the sediments as well as the waters of its tributaries. The currents in such an estuary are periodic, changing with the flood and ebb, and the conditions of deposition vary accordingly. The

Atlantic coast is fringed with estuaries which are carefully mapped by the Coast Survey, but variations of deposit with changes of current have apparently not been described. Writing of the La Plata, an estuary 125 miles long, where the tide from the Atlantic contends with the current of the rivers Paraña and Uruguay, Revy says: [1]

"At this point, where the power of the tidal wave balances that of the rivers, there will be no current; the level of the estuary will rise slowly like that of a lake receiving supply from all round its border. It is here—where the rivers and the tidal wave contend for supremacy, each trying to establish its own current, and where for hours the power of either of them trembles in the balance without any sensible movement in any direction—that deposit copiously takes place; matter, held in suspension by the rivers as long as their currents are maintained agitating their water, is dropped as soon as they come to rest. It is here, within about 10 or 20 miles of the river's mouth that banks are most rapidly growing and islands are forming, and the ultimate result of these daily contests is invariably in favor of the rivers which slowly but steadily encroach on the estuary and ultimately annex its whole territory. The progress of the tidal wave is, however, never checked an instant, the rivers only check the currents originating with the wave. . . . . A tidal wave is never visible to the eye, and can only be conceived from observation, by a successive measurement of its dimensions, which are very large. We may, from an elevated position, see 10 or 15 miles, but a tidal wave on the La Plata is about 258 miles long. . . . .

". . . . During the second half of the tidal wave, viz., from flood to ebb when the surface of the La Plata is falling, there is much more uniformity in the directions of the currents, which for a time will be the same for the whole estuary, all tending to the Atlantic. The wave will again proceed faster in the deeper than in the shallower portions of the estuary, and will accordingly make the level fall a little faster in the deeper channels, and

[1] Op. cit. pp. 29–30.

the current will now set from shore into the estuary; the reverse of what happened with the rise of the La Plata.

"By degrees the level of the estuary will again adjust itself to mean sea-level. All the water which the tidal wave brought from the sea will now have to be returned, and in addition the whole volume which the great rivers have discharged into the estuary; and the currents will not only be stronger, but they will also last longer, of which circumstance the outline of the tidal wave bears evidence, the duration of the rise of the La Plata being about six hours, its fall continuing for about seven hours."

Revy further calls attention (page 23), to the fact that the current with a given fall of the river is swifter in deeper, slower in shallower water therefore deposit during flood-tide is more copious over shallows, and is there less liable to scouring during the ebb. It follows that the shallows become tide-flats, tide-flats are raised to rush-grown islands, and the islands unite to extend the river's banks. Thus the Paraña has filled two-thirds of the La Plata, which was 325 miles long, and the river will ultimately replace the estuary, so that the future delta will be built into the Atlantic, as that of the Mississippi extends into the Gulf.

If the sediment thus deposited consists of mingled sand and clay it will be sorted to some extent by the alternate checking and starting of currents. As with rising tide the current slows, sand will first be dropped; during the period of quiet water both sand and clay will sink together, though at unequal rates; and when the ebb restores the outward current, the surface of the latest deposit may be scoured, removing clay and leaving sand. Furthermore the swifter currents of the channel may carry clay, even though dropping sand, while the slower currents of the shallows drop both. Hence there must be a tendency toward alternation of more sandy layers with more clayey ones, and of horizontal passage of sands into clays.

Where rivers enter bays of such depth or expanse that the fresh water does not displace the salt water, other conditions than those governing estuarine deposition prevail. It is there

probable that the influence of tides is often subordinate to that of winds, of the difference of density between fresh and salt water, of mechanical and chemical reactions of salt water on sediments, and of currents prevailing along shore.

The influence of tides upon undertow, tending alternately to retard and accelerate the seaward current, may be important and may lead to alternate episodes of deposition and scouring as it does in estuaries; this is probably the case on all submerged continental platforms, and particularly where tides sweep in from a great expanse of ocean, as on the Atlantic coast of the United States. The effect, where conditions favor it, would be more regular than among the shoals and channels of an advancing delta, and the alternation of strata would be more distinct and even; it is possible that thinly interbedded strata of unlike character may be thus interpreted.

The well recognized characteristics of tidal formations are the evidences of shallow water, ripple marks, sun cracks, organic trails, etc., peculiar to sections of the shore where sediment is abundant. The strata are shales, and shaley sandstones irregularly bedded and often red. Such deposits are direct evidence that:

(1) The land from which they came presented gentle slopes and was mantled in residual formations to a distance from the sea.

(2) Since the zone of tide-flats along any shore is limited in width, if the distribution of such strata be wide, either great rivers gradually filled a shallow basin, as the Mississippi, the Amazon and Paraña have done, or the sea transgressed upon a low-level land. In the former case the land was built outward by volumes of muddy fresh water, and the deposits would be of fresh or brackish water types. In the latter case the sea prevailed and the deposits would be of marine character.

(3) Since the level of tidal deposits is near the surface of the water, and they are therefore limited in thickness, if a considerable thickness shows the characteristic marks throughout, the area of deposition subsided at a rate approximating to that of accumulation.

(4) Since tidal deposits are imperfectly sorted, they form under shelter from waves or in the presence of waves of force insufficient to handle the volume of sediment. The shelter may be a point of land before a bay or a barrier of beach sand before a lagoon; in either case clean sands and mud deposits may be contemporaneous. Or the feeble waves may be unequal to the task of sorting, because of short fetch in a narrow sea.

(*d*) *Long continued or powerful winds.*—The fall of a river determines its current, other things being constant, and therefore its transporting power. The fall near the mouth is lessened in any given stream if the level of discharge is raised, and vice versa, and the influence of tides in this respect has just been discussed. Winds may exercise a no less important influence. Revy (p. 27) describes an instance in which the effect upon the tides of a storm approaching from the east, combined with its subsequent direct effect in heaping up waters, was to raise the level of the La Plata fifty inches at ebb tide, and to reverse the current of the Paraña for a hundred miles. An extraordinary result like this is probably balanced in its effect upon deposition by the scouring which takes place when the wind changes direction, or calms, and the mass of water returns to its normal level. But the influence of long continued winds blowing periodically during certain seasons of the year must be effective in causing deposition from silt-laden rivers. Humphreys and Abbott briefly discuss the nature of winds affecting the level of the gulf at the mouth of the Mississippi, and assign an important share of the results from deposition to the influence of the southeast winds.[1]

(*e*) *Flotation of fresh water on salt.*—Fresh water is lighter than salt water, hence a river discharging into the ocean rises and spreads over the surface. The volume of the river, advancing, holds back the salt water, and the fresh water flows up an incline which is the surface of contact between the media of unlike densities. This checks the river's current and forms a

[1] Physics and Hydraulics of the Mississippi. Page 450.

vertical eddy or "dead angle," in which material rolled on the river's bottom is left and some sediment is dropped. Thus bars are formed in advance of deltas.[1] With rising tide or on shore winds the elevation of the salt water surface will increase this effect and force the zone of maximum deposition shoreward, while the reflux with the ebb or change of wind will lower the incline and assist wider distribution of sediment. Hence there is most rapid accumulation in the comparatively narrow strip of deposition during rising tide.

Flocculation in salt water.—Acids and salts in solution cause fine particles of sediment to draw together in flocculent form and therefore to settle more rapidly than they would in fresh water. W. H. Brewer states that clay which has been in suspension thirty months in fresh water had not settled out as clearly as the same clay from a solution of common salt in less than thirty minutes,[2] and he describes a number of experiments tending to show that "when a muddy river enters salt water chemical laws interfere with the purely mechanical ones. Then the rate of deposition is affected by the salt more than by the current, and velocities which would be more than sufficient to carry the finer suspended matter indefinitely, if the water were fresh, entirely fail where the water is brackish or salt. Practically it is the degree of saltiness which controls deposition."

Brewer applies this principle to a discussion of the formation of the bars of the Mississippi and concludes that the zone of maximum deposition retreats and advances as the greater or less volume of the river changes the position of the opposing salt water. It is obvious that this condition would be combined with that of the "dead angle" produced by the rise of the fresh water on salt.

The phenomena of flocculation have been attributed by Hilgard, Brewer and Barus to chemical reactions, but Milton Whitney finds a readier explanation in the forces of attraction or

[1] Humphreys and Abbott; op. cit. p. 445.

[2] Memoirs of the National Academy of Sciences, Vol. II, 1883, p. 168.

tension existing among the fine particles of a solid in suspension, which are modified by the presence of salts.[1] But whatever the conclusion may be as to the nature of the controlling law, the influence of salt water in this respect is an important cause of deposition of clays at the mouths of rivers.

(*g*) *Inequalities of depths; lee banks.*—When any volume of flowing water expands, it loses velocity and, if muddy, deposits sediment. This well recognized condition of river deposition has been considered in reference to a river entering a lake; it is equally true of an ocean current or of undertow, where the former passes from a narrow strait to the broader sea, or where either one flows from shallow into rapidly deepening water. The condition needs no explanation—it requires only illustration.

From the Atlantic the southern equatorial current sweeps past the mouth of the Amazon and Orinoco; as the Gulf stream it crosses before the Mississippi delta, and pouring out through the Straits of Florida enters the North Atlantic. From the rivers tributary to its course it receives fine sediment escaped beyond the deltas. In its passage through the Caribbean sea and the Gulf of Mexico it flows over the eastern Caribbean deep, Bartlett's deep and Sigsbee's deep, and where it leaves the Blake plateau north of the Bahamas it falls over the continental rim into ocean depths. Between these basins it traverses relatively shallow seas, whose bottoms are floored with modern limestone and green sand. These deeps of 2,500 to 3,000 fathoms and shoals at 100 to 500 fathoms are result of epeirogenic forces probably, but they are now floored with deposits which consist of the shells of pelagic organisms mingled with terrigenous silt, forming "modified pteropod ooze."[2] This deposition, if it has gone on long enough since the depression at the deeps, or fast enough to mask the details of deformation, possibly continued up to a recent time, determines the profiles of the slopes from shoal to abyss. In

[1] U. S. Dept. Agric. Weather Bull. No. 4, 1892, "Some physical properties of soils," pp. 19–23. Milton Whitney.

[2] Geologic and bathymetric maps of the Atlantic in "Three Cruises of the Blake," by Alex. Agassiz, Vol. I.

the Eastern Caribbean deep the declivities are such as would thus be determined; the northern and southern slopes between which the current flows are approximately equal and steep; the slope of the eastern side is also steep and lies at right angles to the course of the current in the position of a bank forming in the lee of a terrace, and the rise from the abyss westward in the direction of the current is relatively gradual.[1]

This basin is the one most advantageously situated to exhibit slopes of deposition. Bartlett's deep lies like a narrow cañon across the course of the current, and the small triangular basin immediately east of Yucatan, while it shows a steep slope northward in the direction of the current, presents similar declivities along its other two sides which are possibly scoured by the waters converging to pass out at the apex, the Yucatan channel. The steepest slope of the Gulf of Mexico from the 100th to the 2000th fathom line, is in the position of a lee-bank northwest of the Yucatan plateau, and the contours elsewhere are apparently modified by the scouring action of the current as it sweeps around the basin, and by terrigenous deposits from the adjacent shores and rivers. The Blake plateau, over which the Gulf stream sweeps north of the Bahamas, is clean, hard limestone, but a lee-bank of mud and ooze is forming on its short, steep slope into deep water. Agassiz says (p. 277): "There we pass from the comparatively coarse shore mud to finer and finer ooze, which becomes an impalpable silt in the deeper water beyond one or two thousand fathoms, assuming at the same time a lighter color."

Another illustration may be found in the deposits of silt which form the edge of the continental plateau off the North Atlantic coast of America. Agassiz has mapped the width of the plateau as covered with "silicious shore deposits," and examination of some of the samples of bottom in the Coast Survey office, for which opportunity has been most courteously extended to the writer, shows that the surface of the plateau is

[1] See bathymetric map opp. p. 98, "Three Cruises of the Blake."

composed of sands which are indeed fine near the eastern edge, yet are distinctly granular and incoherent. But soundings on the steep slope beyond the 100 fathom line have brought up very fine silt from the bank of which that slope is the surface, and this silt passes at its foot into globigerina ooze. The zone of transition from clean sand to silt is as sharp as the edge of the slope and is coincident with it. It is evident that the suspended mud which escapes beyond the estuaries and sounds of the littoral is swept out until the undertow expands over the edge of the escarpment, and is diffused in deep water; there the silt forms a great bank 10,000 feet high, with a slope of 3 to 8 degrees, which has grown seaward during geological ages, and continues to expand as erosion continues on the land.

The structure of this deposit can only be inferred, but it is worthy of consideration. The surface of accumulation, to which bedding planes are probably parallel, is inclined at a considerable angle, and traverses the bank from top to bottom obliquely to the vertical thickness. The direction of the growth is outward, not upward. The conditions of deposition are similar to those of a delta advancing into fresh water, and the structure of the deposit is probably similar to that shown by Gilbert for a fresh-water delta. (Fig. 14, p. 68, Lake Bonneville). If the detritus was sand, instead of silt, the conditions would be identical, and the bedding which would be exposed by removal of the horizontal upper layers would represent an enormous thickness of strata, inclined at a dip corresponding to the slope of the bank. Russell rejects explanations of the attitude of the Newark beds so far as they are founded on sedimentation,[1] but it seems possible that they may present the structure of lee banks. It may also be probable that isoclinal structure, where repetition of strata does not occur, is evidence of this form of deposition and of the conditions essential to it.

Deposits of this character, consisting usually of clay or silt, are significant of extended rock decay on the land, of currents

[1] Bull. U. S. G. S. No. 85, Correlation Papers.— The Newark System, p. 78. I. C. Russell.

capable of distributing the sediment, and of shoals and deeps in the sea. The amount of difference in depths is not indicated, but the rapid descent from the edge of the bank to the foot is essential to diffusion of the current and the consequent deposition. A lee-bank is a submarine terrace of construction. Where such a terrace extends into an abyss it argues prolonged development, and, therefore, antiquity of relation between continental platform and oceanic basin.

(*h*) *Subsidence from oceanic circulation.*—The greater part of terrigenous sediment must be deposited in deltas and estuaries, on continental platforms, and in silt banks along great deeps. But a very considerable amount of fine silt brought out by rivers and undertow, quantities of volcanic dust fallen on the ocean, and the calcareous and silicious parts of pelagic organisms are taken into oceanic circulation, and find a resting-place more or less remote from their place of origin. These deposits constitute the deep-sea formations; they are not clearly recognized among the strata of past geological periods now exposed in land surfaces, and on this fact rests the principal argument for the antiquity of the continents and oceans. They have been fully described by Murray,[1] and their mode of deposition need here be indicated only by reference to the blue muds of the Bay of Bengal and the Arabian Sea.

The blue muds are composed of minute mineral fragments derived from the disintegration of the land, of a diameter of .05 mm., or less, which may contain calcareous remains amounting to 50 per cent. of the whole, or may be almost free from lime. The description of a typical sample, taken about 275 miles south of the mouth of the Ganges, is given by Murray[2] in an article which is accompanied by a map showing the distribution of different formations. From this map we may gather that terrigenous deposits form a belt, 50 to 125 miles wide, along the eastern coast of Africa, the western coast of Australia, and the Malay

[1] Challenger Reports; Narr. of the Cruise, Vol. I, Part II.

[2] Scott. Geog. Mag., Vol. V, No. 8, Aug., 1889, p. 420. John Murray on "Marine Deposits in the Indian, Southern and Antarctic Oceans."

archipelago, but in the Arabian Sea and the Bay of Bengal they extend to distances of 800 miles from the mouth of the Indus and Ganges, and cover areas of more than 700,000 and 900,000 square miles, respectively. By reference to a map of the ocean currents it may be seen that their courses affect the distribution of these deposits. Sweeping at all seasons past the west coast of Australia and directly toward the east coast of Africa, parallel to which it then diverges, the principal current prevents any extended distribution of sediments in a direction normal to these coasts. But the currents of the Arabian Sea and the Bay of Bengal, flowing alternately east and west around these great embayments, past the mouths of the two great silt-bearing rivers, distribute fine material in suspension throughout the area of their circulation.

CHEMICAL DEPOSITION.

Favorable conditions:

(*a*) Evaporation from an enclosed sea.

(*b*) Precipitation of lime and magnesia from ocean waters, charged by solution from the land, through evaporation, through reaction of salt water on fresh, and through varying atmospheric conditions at the surface of the sea.

(*a*) *Evaporation of an enclosed sea.*—When a limited body of water, such as a lake, is subjected to a change of climate, so that evaporation exceeds precipitation of rain, the volume will shrink, outflow will cease, and the solution of salt will be concentrated. If the process is sufficiently continued the solution will become saturated, first for one salt, then another, and they will be deposited in the order of their insolubility. This process is important as an indication of climatic variation in the past; it has been fully described by Gilbert, Russell and Chatard for Pleistocene lakes and the chemical relations, and these studies suggest the conditions to which appeal must be made to explain the less exact facts known in ancient formations of the kind.

(*b*) *Precipitation from brackish waters.*—The chemical precipitation of lime and magnesia from sea-water is a much mooted question. There are two lines of evidence relating to it which

are apparently opposed. On the one hand, the scientists who have described material obtained by soundings on modern limestone deposits have recognized only organic remains. The Challenger in the open oceans, remote from great rivers, the Coast Survey vessels in the Caribbean, the Gulf of Mexico and off the Atlantic coast, the Norwegian expedition in the North Atlantic and English vessels in the Indian ocean have found calcareous oozes of various kinds and rocky limestone formations, but in every case the calcareous matter is described as composed wholly of the tests of pelagic organisms, many of them of microscopic size. It is known that carbonates of lime and magnesia are to a greater or less extent soluble in waters containing carbonic acid, and that the proportion of these carbonates dissolved in ocean waters is small. According to Dittmar the salts in solution in ocean waters contain 0.345 per cent of carbonate of lime and 3.600 per cent of sulphate of lime,[1] and the ocean is capable of dissolving all the lime poured into it by rivers.[2] This view being accepted, it follows that pelagic organisms, which possess the power of secreting solid carbonate of lime from solution, alone can cause lime deposits. Chemical precipitation is, according to this view, impossible, or, if it occurs, is followed by speedy re-solution, and all limestones deposited under conditions of the existing oceans are of organic origin. On the other hand, there are many limestones, deposited at different periods of geologic time, from Algonkian to the present, including some now forming, which consist of more or less clearly crystalline calcite, devoid of organic structure. If this calcite was originally built into organic forms they have been entirely obliterated. Such limestones do indeed contain fossils which sometimes exhibit more or less crystalline texture, but the occurrence of these organic forms in the holocrystalline matrix only raises the question: If the mass was originally all organic and has undergone secondary crystallization after lithifaction, why was the process so complete in the matrix

[1] Report on the Scientific Results of the Voyage of H. M. S. Challenger. "Physics and Chemistry." Vol. 1, p. 204.

[2] Op. cit. p. 221.

and relatively so ineffective in structures whose delicate anatomy can still be traced even to microscopic details? Thin sections of limestone which show a mass of interferant crystals suggest that this was the primary structure of the rock, and organic remains appear to be foreign bodies which are accidentally of the same substance as the matrix. If this view be correct, then only the alteration of the organic carbonate is the measure of the alteration of the rock-mass. If it can be shown that limestones now forming by chemical precipitation possess a crystalline structure, which resembles that of ancient limestones, the resemblance will constitute a presumption in favor of similarity of origin for the modern and ancient formations. And the fact that limestone is now being precipitated would, if it be established, leave the geologist free to weigh the evidence in the case of any ancient limestone for and against its organic or chemical origin. It is not proposed here to argue that limestones are prevailingly of one origin or the other, but only to show that the assumption of organic origin for all the calcareous deposits of the stratified series is too sweeping. To this end it is desirable to consider the chemical and mechanical conditions which affect the precipitation of carbonate of lime, to estimate the solubility of the carbonate in salt water, to review the conditions under which lime is contributed to, and distributed in, the sea, and to describe several cases of modern limestone formation by precipitation.

Schloesing made a number of experiments on the solubility of carbonate of lime in carbonic acid and water; he thus describes his method and results.[1]

"Experiments:—The method adopted was to cause to pass through pure water, which was maintained at a constant temperature and contained an excess of carbonate of lime, a mixture of air and carbonic acid, of a composition varied at will, but constant, for each experiment; this mixture was constantly supplied until a perfect equilibrium was established between the substances

[1] Comptes Rendus, Vol. 74, 1872, pp. 1552-56, and Vol. 75, p. 70.

entering into the reaction, then the quantities of carbonic acid and of lime were determined in the filtered solution.

"Then to run through the scale of pressures of the carbonic acid from the most feeble to the strongest that could be obtained.

"Then to change the temperature and re-commence anew the series of experiments in order to eliminate the influence of heat.

"The experiments establish the fact that pure water in the presence of carbonate of lime, and of an atmosphere containing a determined proportion of carbonic acid, dissolves simultaneously free carbonic acid according to the law of absorption of gases, neutral carbonate according to the solubility of this salt in water free from carbonic acid, and bicarbonate of lime."

The relation found between the tension of the carbonic acid and the proportion of bicarbonate formed is such that: "Equilibrium being established in the solution, the slightest diminution of the tension of the carbonic acid in the atmosphere determined the decomposition of a corresponding quantity of bicarbonate, with precipitation of the neutral carbonate and the emission of carbonic acid gas."

The veteran chemist Dumas, in an article on the normal carbonic acid of the atmosphere, says:[1]

"In recent times, by a happy application of the principle of dissociation, M. Schloesing has shown that the proportion of carbonic acid contained in the air was in relation with that of bicarbonate of lime held in solution in the waters of the sea. When the amount of carbonic acid (in the air) is diminished the bicarbonate of the lime in the sea is dissociated, the half of its carbonic acid passes into the air, and the neutral carbonate of lime is precipitated from solution" ("deposé").

Another condition which may decompose bicarbonate of lime is simple mechanical agitation of the water holding it in solution. Dittmar in examining samples of ocean water for car-

[1] Comptes Rendus, Vol. 94, 1882, p. 70.

bonic acid, was led to make a series of experiments on the effect of shaking with air an artificial sea-water, containing a known amount of carbonic acid. He found that he shook out 27 per cent of the carbonic acid originally present, and this did not represent the greatest possible loss. After describing the experiments he says :[1]

"The experiments reported in this chapter . . . are sufficient to prove . . . that, supposing a sea-water which contains its carbonic acid as bicarbonate, associated or not with free carbonic acid, to be exposed to the air even at ordinary temperature, such a water will soon lose not only its free but part at least of the loose carbonic acid of the bicarbonate (*i. e.*, of what is present over and above that existing in the form of normal carbonates)." Dittmar also discusses the dissociation tension of bicarbonates in sea-water and suggests that the water of the tropics constantly gives out carbonic acid to the air, and water of cooler and of arctic zones constantly absorbs it.[2]

Thus the chemists describe two conditions under which bicarbonate of lime may be decomposed into neutral carbonate and carbonic acid: 1st, by diminution of the tension of the carbonic acid in the atmosphere; 2d, by agitation of the solution.

Theoretically, either one of three things may occur to the neutral carbonate of lime if it be thrown out of solution by either one of these processes, which we may admit are active on some portions of the salt water surface. The carbonate may be redissolved, or deposited as a calcareous mud, or built into organic structures. We may discuss these alternatives in turn.

The solvent action of sea-water has been the subject of direct observation in the ocean and of experimental determination. Deep-sea shells, dredged from the bottom of the Pacific and now in the Smithsonian collection[3] are corroded, some of them on the outside only, some of them through and through. In the former

[1] Report on the Scientific Results of the Voyage of H. M. S. Challenger. "Physics and Chemistry," Prof. Wm. Dittmar, F. R. S. Vol. I, p. 115.

[2] Op. cit., pp. 212-213.

[3] For an opportunity to examine these my thanks are due to Dr. Dall, B. W.

case the creature still inhabited the shell and preserved the essential parts of its house; in the latter case the decomposition of the fleshy parts may have assisted the solution of the calcareous skeletons. To this last point Murray calls attention:[1]

"It is probable, however, that carbonic acid does play an important part in the solution of shells of animals sinking through the water. The organic matter of the animal on being oxidized produces carbonic acid, which, being itself liquid at all depths over 200 fathoms, will form a locally concentrated acid solution inside the shell, which it will attack with vigor."

The shells which were corroded while still inhabited were also exposed to unusually active solvent influences since they lay upon the bottom, of which Agassiz writes:[2]

"The pelagic animals derive a large part of their food supply from the swarms of large and small pelagic algæ covering the surface of the sea in all oceans. On dying, both surface animals and plants drop to the bottom, and still retain an amount of nutritive matter sufficient to serve as food for the carnivorous animals living on the bottom. A sort of broth, as it has been called by Carpenter, collects on the bottom of the ocean, and probably remains serviceable for quite a period of time; the decomposition of the organic material which has found its way to the bottom takes place gradually, and its putrefaction must be very slow." Thus these more or less corroded shells, dredged from the deep sea, bear witness to the solvent evolved in a bottom layer of decomposing organic matter.

A more direct line of evidence as to the solvent action of the sea-water itself is afforded by observations on the depths to which calcareous skeletons will sink undissolved. The pelagic pteropods and foraminifera, living at the surface, sink on dying and are slowly dissolved; if the water be too deep they never reach bottom. The limits below which they are not found are about 1500 fathoms for pteropods, thin shells exposing large

[1] Narrative of the Cruise of the Challenger, Vol. I, Second part, p. 981.

[2] Three Cruises of the Blake, Vol. I, p. 313.

surfaces to solution, and 2800 for globigerina, smaller shells, relatively more massive. Commenting on this, Dittmar says:[1]

"At the greatest depths of the oceans all these calcareous shells disappear from deposits in all latitudes. The cause of this, in my opinion, is not that deep-sea water contains any abnormal proportion of loose or free carbonic acid, but the fact that even alkaline sea-water, if given sufficient time, will take up carbonate of lime in addition to what it contains."

The solvent action indicated by the disappearance of delicate and microscopic shells, which enclose decaying organic matter, yet sink through 9000 to 16,000 feet of water, is very moderate.

Dittmar says:[2] "Sea-water is alkaline; all the alkalinity must be owing to carbonates, and of these carbonate of lime is one." Now the very moderate solvent power of this alkaline solution may be satisfied so far as carbonate of lime is concerned by two sources—by organic tests in suspension, and by chemical precipitate. The lime used by organisms is derived from the solution to which it is partly returned by re-solution, but another part is deposited, and the sea thus suffers constant loss. This loss is supplied by the land. If this terrigenous supply is less than the amount of organic deposit the sea will become less alkaline, and will more efficiently dissolve calcareous tests until the solvent is satisfied. If the land contribution is continuously equal to the amount organically subtracted, there will be equilibrium. If the land yields more carbonate of lime than that which is being locked up in organic limestones, the alkalinity of the sea will gradually increase until there is chemical precipitation. This condition is favored by the entrance of lime-bearing fresh water into a sea free from active currents and exposed to evaporation which balances the inflow.

Since the amount of lime in the ocean is thus balanced between that contributed by the land, and that precipitated by organic or chemical means, it is worth while to review the con-

[1] Op. cit., p. 221.

[2] Op. cit., p. 206.

ditions under which lime is carried from the land, and to consider how it is distributed in the sea. As was stated early in this paper, the amount of lime carried annually from a given land area is directly related to the efficiency of rock-decay; rock-decay is most efficient over surfaces which have suffered prolonged degradation, and on such surfaces the development of drainage systems has usually resulted in the growth of great rivers. Hence the lime contributed from continents to oceans is delivered chiefly at a few places, the mouths of extended systems, and there is great inequality in the distribution of these along different coasts and among different seas. Of this fact South America is the most conspicuous example, with all its great rivers pouring into the Atlantic, and not one considerable stream entering the Pacific. More limited seas, which receive vast quantities of solutions are the Caribbean and Gulf of Mexico, Arabian Sea, Bay of Bengal and Yellow Sea.

At the mouths of great rivers there exist several conditions which influence the solubility and distribution of lime in the adjacent seas; these are: 1st, the amount of lime in solution in the river water; 2d, chemical reactions between substances in fresh and salt water; 3d, the relative solubility of lime in fresh and salt water; 4th, the conditions of evaporation and agitation of the brackish water; 5th, the effects of currents.

The proportion of solids in solution in a river is dependent not only on the extent and slopes of its basin, but also on the nature of the rocks exposed, and the influence of climate on decay. Under like topographic conditions, silicious schists and a cold climate probably yield a minimum contribution; crystalline rocks and a warm, moist climate yield more; limestone areas, though resistant in a dry climate, suffer most rapid degradation under a humid atmosphere, and the deposits of the later geologic periods, including as they often do quantities of soluble salts, charge the drainage most strongly. The following analyses present specific contrasts, traceable to these geologic and climatic conditions. Each analysis represents but one phase of composition, which varies in each river with high and low

stages, and the analyses of our great rivers are incomplete, but, strange as it seems, no other analyses of their waters have been found, after diligent search.

SAMPLES.

(*a*) Ottawa river; sampled March 9, 1854, before the melting of the snow, at head of St. Anne lock; water was pale amber yellow, free from sediment and derived from a region of crystalline rocks covered with forest and marsh vegetation.[1]

(*b*) St. Lawrence river, sampled March 30, 1854, before the melting of the snow, on the south side of the Pointe des Cascades, Vaudreuil; water was clear, colorless, and represents the drainage of areas of glacial drift, crystalline rocks and paleozoic sediments, clarified by passage through great lakes.[1]

(*c*) Mississippi river;* sampled in the autumn of 1887 at very low water, in the main channel above the mouth of the Missouri; water represents drainage from areas of glacial drift, crystalline rocks and paleozoic sediments, including large expanse of limestone and cultivated lands.

(*d*) Missouri river;* sampled on the same day as the preceding; water represents drainage most highly charged with the soluble salts of the more recent and little consolidated geologic formations; potash was no doubt present but was not determined.

(*e*) Mississippi river;* six miles below the mouth of the Missouri; sampled on the same day as the preceding in the current of Mississippi water as shown by a float dropped on taking sample *c;* sample represents Mississippi and Missouri waters, apparently with excess of the latter.

(*f*) Mississippi river;* twelve miles below the mouth of the Missouri, above St. Louis; sampled on the same day as the preceding in the current indicated by the float; sample represents Mississippi and Missouri waters apparently more thoroughly mixed.

[1] Geology of Canada, 1843-63, Logan, pp. 565-568.

*Annual Report of the Water Commissioner, St. Louis, 1888, pp. 309-310. Analyses by St. Louis Sampling and Testing Works, Wm. B. Potter, Manager.

ANALYSES—PARTS PER 1,000,000 OF WATER.

Constituents.	Ottawa. *a*	St. Lawrence. *b*	Mississippi. *c*	Missouri. *d*	Missouri and Mississippi. *e*	Missouri and Mississippi. *f*
Total Solids	------	------	253.69	1207.66	1058.98	787.12
Filtered sediment	69.75	167.80	20.90	638.26	622.33	389.36
K	1.52*	1.15*	not given	not given	not given	not given
Na	2.39*	5.03*	3.37*	12.76*	9.16*	10.37*
MgO	2.36*	12.08*	28.26	41.96	37.51	39.40
CaO	13.88*	44.92*	52.93	110.15	109.63	94.90
Cl	.76	2.42	5.31	19.53	14.22	15.93
SO_3	1.61	6.87	10.28	89.76	73.66	69.89
SiO_2	20.60	37.00	not given	not given	not given	not given
	69.75	167.80	20.90	638.26	622.33	389.36
Iron and alumina	traces	traces	none	55.84	20.90	26.80

According to Gooch[1] the combination in these analyses should be calculated in the order KCl, NaCl, K_2SO_4, Na_2SO_4, $Mg SO_4$, $CaSO_4$, $MgCO_3$, $CaCO_3$ Na_2CO_3, etc.; and this is the order followed in the Canadian analyses. Hence the following is the hypothetical combination.

	a	*b*	*c*	*d*	*e*	*f*
Total Solids	-----	------	253.69	1207.66	1058.98	787.12
Filtered sediment	69.75	167.80	20.90	638.26	622.33	389.36
KCl	1.60	2.20	not given	not given	not given	not given
NaCl	-----	2.25	8.57	32.03	23.30	26.38
K_2SO_4	1.22	------	not given	not given	not given	not given
Na_2SO_4	1.88	12.29	not given	not given	not given	not given
$Mg SO_4$	none	none	15.41	125.90	118.49	104.83
$Ca SO_4$	none	none	none	9.93	none	none
$Mg CO_3$	6.96	25.37	19.63	none	1.37	4.28
$Ca CO_3$	24.80	80.83	94.56	189.35	195.79	169.47
Na_2CO_3	4.10	0.61	none	none	none	none
$Fe_2O_3 +$ Al_2O_3	traces	traces	none	55.84	20.90	26.80

The chemical reactions which take place between substances dissolved in river waters and those contained in salt water are no doubt complex; but that which is most significant in relation to possible precipitation of carbonate of lime depends upon the fact that organic matter may decompose sulphate of lime. Ac-

* Calculated from combinations given in the original publications.

[1] Analyses of Waters of the Yellowstone National Park, Bull. U. S. G. S., No. 47, p. 24.

cording to Dittmar,[1] the greater part of the lime in ocean water is there combined as sulphate, which in contact with organic matter would be reduced to sulphide with evolution of carbonic acid; the latter would attack the sulphide with formation of carbonate of lime and sulphide of hydrogen. Thus organic matter in river waters tends to increase the proportion of *carbonate* of lime in the zone of brackish water. The carbonate thus formed is added to that already existing in the river water.

The solubility of carbonate of lime in fresh water and in salt has been an object of consideration by several experimenters. Sterry Hunt testing artificial solutions found that 1 litre of water which contained 3 to 4 grams of sulphate of magnesia could dissolve 1.2 grams of carbonate of lime and 1 gram of carbonate of magnesia; but after standing a long time all the lime was deposited as hydrated carbonate.[2] Thus it would appear that the presence of the sulphate assisted the solution of the carbonates.

Experiments made by Daubrèe, which contradict Hunt's results, led Thoulet to conduct a series to determine the question.[3] He took several minerals, marble, shells, coral and globigerina ooze, and subjected the comminuted samples of each separately to the action of filtered ocean water and distilled water during five weeks in each case. The solutions were shaken several times each day and the water was changed from time to time. At the close of the experiments the samples had lost in weight and the amount taken into solution, reduced to that dissolved per cubic decimeter per day, was found to be, in grammes

	In ocean water.	In fresh water.
Shells, - - - - - -	.000039	.001843
Coral, - - - - - -	.000201	.003014
Globigerina, - - - - -	.000137	.003091

[1] Op. cit., p. 204.

[2] Dittmar, op. cit., p. 209.

[3] Oceanographié (Statique) par M. J. Thoulet, 1890, p. 263, and Comptes Rendus, t. CVIII, April, 1889, p. 753.

"One sees that the solubility in ocean water, itself very feeble, is also notably more feeble than the solubility in fresh water."

When river water enters salt water it is exposed in different form and under different physical conditions from those which existed in the river. As the fresh water is lighter than the salt, it floats upon it and spreads out in a sheet not unlike a fan. As compared with its depth and width in the river the layer is very shallow and widens from the mouth. Through waves and currents the fresh and salt water mingle, and the expanse of brackish water may be of great extent. Forchhammer attributes the minimum salinity which he found for surface water from the north Atlantic, 900 miles from the mouth of the St. Lawrence, to the volume of that river, and he found the ocean water freshened at a similar distance from the La Plata. This thin sheet of brackish water is exposed to variations of temperature and barometric pressure produced by changing winds, now on, now off shore, and is in constant agitation with the rise and fall of waves. Thus the conditions which produce varying tension of carbonic acid, and which aid the escape thereof, exist at its surface, and the bicarbonate of lime in solution must be in unstable equilibrium, with constant formation of neutral carbonate and more or less constant recombination of it. If the neutral carbonate be present in sufficient quantity it will remain in suspension, undissolved and unused by organisms, and will ultimately be deposited as calcareous ooze.

Oceanic circulation maintains an approximately uniform composition of ocean water in all parts of the open seas, and great currents sweeping past river mouths distribute the contribution of fresh water and its solid matters, whether in solution or suspension. Thus the lime brought down by rivers, though measurable by hundreds of thousands of tons per annum, is so widely diffused in the vast volume of the ocean that it escapes recognition.

There are, however, several instances of modern limestone formation which, though local, illustrate the processes of chemical deposition on a large scale. The descriptions of these may

close these suggestions concerning limestone deposition by other than organic means.

Chemically deposited limestone is forming in the southern part of Florida, probably over extensive areas. The Everglades, 4,000 to 5,000 square miles in extent, lie nearly at sea level, margined by barrier reefs which confine the surface waters; in the dry season the drainage consists of numerous small streams—in the wet season the region is all submerged save the numerous muddy islands. Explorations on the western side, from Cape Sable north to Punta Rasa, were made by Mr. Joseph Wilcox, whose observations are stated by Dall as follows:[1]

"At the north end of Lostman's Key (on the west coast, in about latitude 25° 30′) they entered the river of the same name and succeeded in penetrating 12 or 15 miles inland. No hard ground was seen except near the mouth of the river, and the highest land at the latter place was not over 3 feet above high tide. Wide, shallow bays, with muddy bottom, interspersed with low, muddy mangrove islets, comprise the scenery. The boat frequently grounded, and was obliged to wait for the rise of the tide. A small fresh-water stream was finally reached, the current of which had scoured a channel 4 to 6 feet deep, with a rough, hard, rock bottom, fragments of which were broken off. It consisted of large masses of Polyzoa more or less completely changed into crystalline limestone, the cavities filled with crystals of calcspar. The rock is very hard and compact."

"Allen's creek, emptying into Walaka inlet, an arm of Chukoliska bay, was also visited. At a point 8 or 10 miles east from the Gulf of Mexico the party were able to land on soft, wet soil, a little higher and drier than that at the head of Lostman's river. A third of a mile eastward from the head of the creek specimens were obtained of a few rocks which project above the soil. They presented molds of recent shells with the interior filled with calcspar, and an occasional *Pecten dislocatus* or *Ostrea virginica*, still retaining its shell structure. The cavities between the shells

[1] Bull. U. S. G. S. No. 84. Correlation Essays—"Neocene," by Wm. H. Dall, pp. 99–101 and 154.

were filled with hard, coarsely crystalline limestone. The rock was not coquina modified, but looked more like a fossilized oyster reef. It contained no corals, and was obviously Pleistocene. The rock formed the base of small islets of drier soil amid the marsh, on which islets grew pine trees. The marsh, apart from these islets, is probably entirely submerged in the rainy season."

In the bulletin referred to Dall speaks of the rock obtained by Willcox as being of organic or of partly organic and partly chemical origin, but at the time that manuscript was prepared the observations were less complete than now. In a recent letter he says: "Mr. Willcox's observations on the deposition of the flocculent mud from lime-bearing water were later than the original statement. The precipitated mud is more or less mechanically mixed with masses of the corrallia of Polyzoa and bivalve shells driven in shore by the sea, but these creatures do not live in the muddy water, but in the clearer water outside."

Through the courtesy of Dr. Dall the writer has examined specimens of this rock. It is a light cream-colored mass of crystalline calcite formed around the included fragments of shells. Under the microscope the unaltered structure of the organic fragments is strikingly different from that of the coarse holocrystalline matrix, in which it is apparent that the crystals developed in place. Were this a limestone of some past geologic period it would be concluded, on the evidence of the crystalline texture of some parts of it, that it had been metamorphosed and that the organic remains now visible had escaped the process which altered the matrix. But the observed conditions of its formation preclude the hypothesis of secondary crystallization. Apparently, the crystalline matrix is one primary product from solution, a rock formed in contact with the bottom, the calcareous mud is another, which, being precipitated in the solution, remains an incoherent sediment.

These results may perhaps be thus explained: The drainage of the peninsula contains an unusually large amount of lime, in consequence of the abundant supply of carbonic acid and other products of vegetable decay in the sub-tropical climate and

of the calcareous nature of all the rocks of Florida. In the Everglades this water is exposed in broad shallow sheets to active evaporation, agitation and variations of atmospheric temperature and pressure. Concentration of the solution and escape of carbonic acid, including some of that in the bicarbonate in solution, follow, and the neutral carbonate is produced in excess of the amount that can be retained in dissolved form. It is therefore precipitated in two forms—first, from the mass of the water as a flocculent mud ; second, from the lower layers of the water in contact with limestone as crystals forming an integral part of the solid rock.

The alternation of dry and wet seasons is accompanied by concentration and sluggish flow, alternating with dilution and flood currents. Therefore there are seasons of more active precipitation interchanging with those of more vigorous transportation and, perhaps, partial re-solution. In these latter seasons the calcareous mud is swept beyond the shallow basin where it forms, and enters as a suspended sediment into the Gulf circulation. What part, if any, is dissolved, what is deposited as mud in the lagoons along the coast, and what is swept into the silt banks of the Atlantic, is not known.

Conditions which produced similar results are described by Gilbert as having existed in Lake Bonneville.[1] Tufa was deposited on the shores of the lake at various stages, but most abundantly at the Provo stage, during which the water lingered longest at one level. The occurrences are thus described:

"The distribution of tufa along each shore is independent of the subjacent terrane. . . . . . No deposit is found in sheltered bays, and on the open coast those points least protected from the fury of the waves seem to have received the most generous coating. These characters indicate, first, that the material did not have a local origin at the shore, but was derived from the normal lake water ; second, that the surf afforded a determining condition of deposition."

[1] Monographs of the U. S. G. S. Vol. I, p. 167-168.

Dittmar's experiments in decomposing bicarbonate of lime by agitation indicate the nature of the condition afforded by the surf, and it appears that the neutral carbonate is capable of lithifying at the point of, and immediately upon, separation. Gilbert also says that: "Calcareous matter constitutes an important part of the fine sediment of the lake bottom, and this was chiefly or wholly precipitated from solution," and to explain the formation of the coherent and incoherent deposits of the same material from the same water he suggests that "separation was promoted by aëration of the water. All precipitation being initiated at the surface during storms, coalescence at the shore may have resulted from contact at the instant of separation."

Mr. Gilbert states (pp. 178-179), that the concentration of the waters of Lake Bonneville at the Provo stage is not definitely known. The lake had an outlet at the northern end of Cache bay, and the principal tributary, Bear river, emptied into this bay near the outlet. Cache bay was connected with the main body of the lake only by a deep but narrow strait, and it is possible that evaporation from the greater expanse of the lake exceeded the inflow of fresh water into it, while the overflow at the outlet was supplied by Bear river. In that case there would have been circulation through the strait between Cache bay and the main body, an upper current from Cache bay and an undercurrent from the lake. The straits were the scene of peculiarly copious deposition of tufa.

The tufa deposited in Lake Bonneville is of the variety described by Russell as "lithoid tufa,"[1] "of a compact and stony structure" and he concludes that it was formed when the lake waters were moderately concentrated (pp. 210-222). A limestone of similar structure is now forming on the shores of Florida, where the waves break on the beaches under conditions quite like those which determine the growth of tufa, where the surf dashed against the shores of Lake Bonneville. This rock is deposited in irregular layers, sometimes three or four feet thick, on the quart-

[1] "Geological History of Lake Lahontan," p. 190.

zose beach sands. Like the tufa, it is independent of the material upon which it gathers, but the possibility of a local supply of lime exists in the discharge of surface waters below low tide. Under the microscope the material shows a dense, fine-grained groundmass of lime with admixture of fine clay, including grains of quartz and cavities filled with coarsely crystalline calcite.

A case, which is probably more typical of what may occur now, or may have occurred in past ages at the mouths of rivers and in shallow seas, is that of the limestone deposited beyond the delta of the Rhone. This is referred to by Thoulet,[1] and is described by Lyell,[2] who says: "In the museum at Montpelier is a cannon taken up from the sea near the mouth of the river, imbedded in crystalline calcareous rock. Large masses also are continually taken up of an arenaceous rock, cemented by calcareous matter, including multitudes of broken shells of recent species." Lyell attributes the precipitation of lime to evaporation of the Rhone water, which, when it is spread upon the salt water, he compares to a lake. But this one cause is no doubt combined with the chemical and mechanical conditions which have been suggested in the preceding discussion. These conditions are favored at the mouth of the Rhone by the salinity of the Mediterranean and the absence of strong currents.

The examination of a few thin sections of limestone of different ages, from Cambrian to the present, shows that they have three principal types of structure. There are those which resemble the Everglades limestone in that they consist of more or less coarsely crystalline calcite, yet include unaltered organic remains. Of these the Trenton limestone and the marbles of corresponding age in Tennessee, which occur interstratified with unaltered calcareous shales, are the most striking examples examined. Cambrian limestones and the Knox dolomite show similar crystalline structure. The second type, the precipitated sediment which forms the muds of the Everglades and which was deposited in Lake Bonneville is represented by specimens

[1] Op. cit., p. 270.

[2] Principles of Geology, Vol. I, p. 426.

composed of exceedingly fine grained, apparently pulverulent, material; the best of these are from the Knox dolomite and the Solenhofen lithographic stone. The third variety of limestone consists of the thoroughly crystalline marbles, which contain no unaltered material, and which occur in such field relations that they are known to be completely metamorphosed. Extended study is required to determine the nature of deposition of the first and second types. They may have been organic and have suffered moderate alteration only, but there is a reasonable presumption that they did to some extent crystallize in place from sea-water, and were, to a still greater extent, precipitated from the outspread fans of fresh water, radiating from rivers' mouths, whence they spread as fine silt over the bottom of the sea.

ORGANIC DEPOSITION.

Since deposits of this character are composed chiefly of the calcareous or silicious remains of marine organisms, their formation is conditioned primarily by the circumstances controlling marine life, and secondarily by the insolubility of the skeletons under circumstances of wide distribution and gradual sinking.

Favorable conditions.—(*a*) Warm waters.

(*b*) Clear waters.
(*c*) Abundant food supply. } Conditions favorable to life.

(*d*) Depths less than 1500 fathoms.

(*e*) Expansion and diffusion of currents in rapidly deepening water.

For a description of the oceanic deposits and of the biological conditions which promote their accumulation, the reader may be referred to the Narrative of the Challenger Expedition, Vol. I, second part, pages 915 to 926. The oozes which are characterized by the predominance of remains of globigerina, pteropods, diatoms or radiolaria are there described, and it is shown that the nature of the deposit is determined by the conditions of temperature, light and motion which favor the generation of multitudes of the minute creatures whose living forms swarm at the

surface of the sea, and whose remains only enter into deposits when they have escaped being used by other creatures, or being dissolved in the ocean waters.

Agassiz, writing of the physiology of deep sea life,[1] points out that in marine, as in terrestrial, life the primary source of food for animals is in plants. The lower types of marine life, it would seem, must derive their sustenance from the water, as land plants get theirs in part from the air, and the silica and lime thus absorbed is taken directly from solution; but the creatures which live on these forms, and the carnivorous animals that feed on them, may get their lime and silica at second hand by digesting and assimilating that which the lower types take from solution. Thus the solids built from solution into organic tests may go through numberless changes before they come to rest on the bottom.

Without pursuing the discussion of biological conditions favorable or unfavorable to deposition, and without entering upon the question of coral formations, which are rarely of prominent interest in stratified deposits, the writer wishes to consider only the circumstances of limestone formation from organic remains, as that from chemical precipitates has been considered.

In discussing the solubility of shells in sea-water it has been pointed out that the layer of organic matter which accumulates at the sea bottom contains a solvent formed by the evolution of carbonic acid in the process of decay. Through this layer all substances must pass before they can become part of a lithified stratum; if they are plant tissue or flesh they will become more or less oxidized; if they are calcareous tests they will be more or less completely dissolved, and, if there be any chemically precipitated lime, arriving on the sea bottom it, too, would be dissolved in this menstruum. The earlier forms of dredge which scooped into the sea bottom, brought up a mass of ooze, formed of fine particles, burying organic forms. The later forms of dredge, arranged to skim the surface of the bottom, bring up

[1] Op. cit., pp. 312–313.

shells and organisms remarkably free from mud. Now it may be conceived that the layer of mud on which the creatures live, die, and with sunken organic remains decay, grades from the fresh surface of recent accumulations downward into a much more completely decayed and dissolved mass, and that this rests upon a surface of limestone. In the upper part of this unconsolidated stratum carbonic acid may most abundantly be evolved; in its lowest part the more concentrated solution of lime may accumulate. Then it is conceivable that lithifaction by crystallization of the carbonate of lime from the more concentrated solution is constantly proceeding on the limestone surface. If this conception be correct the formation of limestone by organic means involves the re-solution and crystallization of more or less of the calcite in the primary formation, and only those organic forms can remain unchanged which resist the solvent action. If they are delicate, as the trilobites' branchia from the Trenton limestones, described by Walcott, they give evidence that they were rapidly buried and protected.

It is thought by some that limestones are evidences of organic life at whatever period of sedimentary history they were deposited, but it has here been shown that the source of all lime in the sea is the land, and that, under conditions existing in certain localities, both crystalline limestone and calcareous mud are now forming chemically. It has also been shown that lime converted into organic forms is subtracted from that which would otherwise go to saturate the sea-water. If, then, in any early age of the earth's history, lime-using organisms were not present to subtract and deposit lime from sea-water, and if the atmospheric agencies worked then as now, the contributions from the land must have continually added to the alkalinity of the sea until chemical precipitation occurred. Such a process must have been limited to seas rather than extended to oceans, because the conditions of delivery of lime from the land were then, as now, localized. With the development of marine life and the increased demand for lime for organic use, and with the corresponding deposition of organic limestone, the sea-water must have become

less alkaline and the conditions of chemical precipitation must have been still more restricted. In time it might occur that pelagic organisms should demand so much lime for circulation from the water to calcareous algæ, to herbivorous and then to carnivorous forms, and so back into solution, that lime could escape from solution by precipitation only under exceptional conditions. If it be true that the oceanic oozes, the muds of the Caribbean, the mud-flats of Florida, and similar calcareous deposits in different seas the world over, be wholly organic, then marine life has locked up more lime than the continents could concurrently supply, and the balance is now turned against chemical precipitation. But it has not always been so.

BAILEY WILLIS.